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SURFACE MODIFICATION ON ALUMINIUM ALLOY BY ELECTRICAL DISCHARGE MACHINING IN DIELECTRIC FLUID OF MONOETHANOLAMINE

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ABSTRACT

Surface modification on aluminium alloy was studied by electrical discharge machining (EDM), using a titanium tool electrode in dielectric fluid of monoethanolamine (MEA). The morphology, element composition and compound of surface modification were characterized by scanning electron microscopy, electron dispersion spectroscopy and X-ray diffraction. The results revealed that the major layer was mainly aluminium titanium nitride (AlTiN) with 45 microns average thickness, showing inhomogeneous solidification, micro cracks and micro voids. In addition, the average surface roughness of the top EDM surface was also evaluated and studied including the microhardness investigation of the layer andthe aluminium alloy substrate.

KEYWORDS: Surface Modification, Electrical Discharge Machining, Monoethanolamine, Average Surface Roughness & Micro Hardness Testing

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Original Article

1. INTRODUCTION

Surface modification is the treatment of modifying and improving the material surface of a workpiece or substrate. It has been widely applied to tooling, equipment, moulds, dies and automobile parts to improve and enhance the physical, mechanical and chemical characteristics of the material surface. Surface modification process is an important process in the industrial world. Its process can be applied to improve the hardness, wear rate, conductivity, anti-corrosion and oxidation resistance on a surface including sustaining its properties for high temperature application. There are several methods of surface modification, such as Physical Vapor Deposition (PVD), Chemical Vapor Deposition (CVD), Magneton Sputtering (MS), and Electrical Discharge Machining (EDM), etc.

EDM is one of the interesting methods of surface modification. It can be used for material removal and surface composition or coating application [1–3]. EDM is generally used in industry for moulds, dies, automobile parts, equipment and tools due to being a highly efficient process with low cost. There are many works using EDM for surface modification, both of binary and ternary hard coatings to enhance the endurance and long life of working parts in application. EDM is a non-contact process, which has a fine gap between a tool electrode and a workpiece allowing sparking in the gap to remove material via a flow of dielectric. [1–5].

Aluminium, known by the symbol Al, is a silvery white, lightweight, soft, durable, nonmagnetic, ductile and functional metal. These properties make aluminium one of the key engineering materials. Normally, aluminium material used in most applications is aluminium alloy [6]. However, aluminium alloy has a problem in terms of hardness and wear rate. The surface modification of aluminium alloy enhances the added value of it, since

it can improve the properties for a particular application. For this reason, the surface modification on aluminium alloy substrate is interesting for improvement, and EDM is an attractive method for this research.

Surface modification for a desired functional behaviour has been reported as possible by EDM in which metal of the tool electrode is transferred to the machined surface [7]. The composite material of the electrode could also improve the mechanical properties on the workpiece surface layer in hydrocarbon oil [8]. By mixing titanium powder to hydrocarbon oil as dielectric fluid, the hardness and microcracking on a machined surface layer could be improved [9]. By adding urea, a white crystalline granular material into the dielectric fluid of distilled water in EDM process using an electrolytic copper (Cu) electrode, B.H. Yan et al obtained a titanium nitride (TiN) hard layer on the substrate, exhibiting wear resistance improvement on the machined surface [10], while Muttamara A. and Fukuzawa Y. achieved a TiN layer by EDM in liquid nitrogen on work surfaces of carbon steel, pure iron and cast iron, respectively; a titanium carbonitride (TiCN) layer was also obtained on both carbon steel and cast iron workpieces [11]. T. Tamura succeeded in developing surface modification of cemented carbide by EDM to eliminate surface defects, including recasting a layer to improve the surface integrity for tool life time [12]. Houqun Xiao et al. studied TiCN coating by using EDM in dielectric fluid of aqueous ethanolamine solution to improve hardness on a surface including bonding strength [13]. Additionally, Amoljit Singh Gill and Sanjeev Kumar studied the surface alloying with powder metallurgy tool electrode by EDM to increase the microhardness when compared with base material [14]. Tsunekawa et al. studied surface modification of aluminium with a Ti electrode by electrical discharge alloying in hydrocarbon dielectric fluid, TiC and TiAl were formed as composite layers [15].

In this work, the surface modification of aluminium alloy substrate is studied by EDM with a titanium tool electrode in dielectric media of monoethanolamine liquid. The morphology, element composition and compound of the surface modification on aluminium alloy material are characterized by scanning electron microscopy (SEM), electron dispersion spectroscopy (EDS) and X-ray diffraction (XRD). Furthermore, the roughness of surface modification is studied, and the microhardness of a cross-section of modified surface is also analysed and compared with aluminium alloy substrate by the microhardness testing machine.

2. MATERIALS AND METHODS

2.1 Surface Modification Preparation

A Mitsubishi EA8-Advance EDM machine was used for the surface modification in the experimentation. The schematic diagram of the electrical discharge machining is shown in Figure 1. Titanium bar grade 1 (10x10x120 mm.) was used as the tool electrode, and chemical composition is shown in Table 1. The aluminium alloy (grade 5083) with a dimension of 100 x 120 x 6 mm. was used as a workpiece or substrate. The chemical composition of the workpiece was examined by EDS with a Field Emission Scanning Electron Microscope (FE-SEM, JSM-7800F, JEOL, Japan) and is shown in Table 2. The dielectric fluid was monoethanolamine liquid ($OHCH_2CH_2NH_2$). EDM area was directly flushed using a circulation pump to maintain stable spark conditions. The electrode and workpiece were cleaned with a mixture of acetone and isopropyl alcohol (50%/50%) by wiping before experiment.

Based on the reviews of many EDM papers and experiment attempts, the current, pulse duration time and duty factor are significant parameters and influence the surface modification in terms of surface morphology. EDM conditions of experiment are shown in Table 3, selecting current 10 A and on time 200 μs.

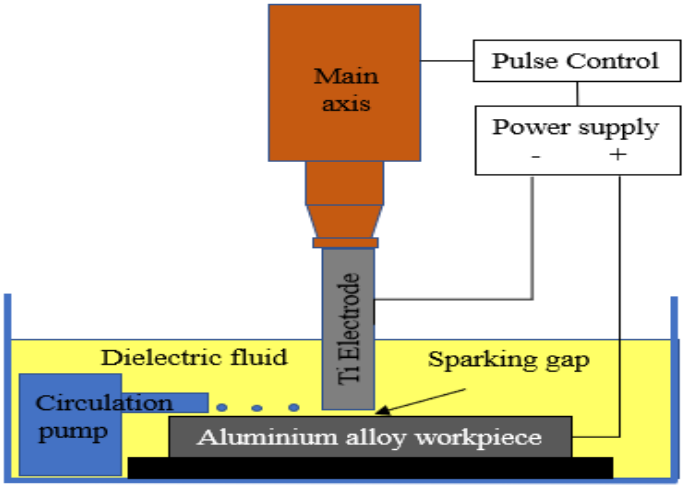


Figure 1: Schematic Diagram of Electrical Discharge Machine.

Table 1: The Chemical Composition of Titanium Electrode

The chemical Composition of Titanium Electrode						
Material	**Elemental Composition (wt.%)**					
	Ti	**Fe**	**O**	**C**	**N**	**H**
Titanium Electrode	99.5	0.2	0.18	0.1	0.03	0.015

Table 2: The Chemical Composition of Aluminium Alloy

The Chemical Composition of Aluminium Alloy					
Material	**Elemental Composition (wt.%)**				
	Al	**C**	**O**	**Mg**	**Mn**
Aluminium alloy	69.12	14.2	9.19	7.02	0.42

Table 3: Electrical Discharge Machining Condition

Parameters	Details
Electrode	Titanium
Workpiece	Aluminium alloy
Dielectric fluid	Monoethanolamine
Polarity of Ti-electrode	Negative (-)
Polarity of workpiece	Positive (+)
Reference voltage (V)	250
Pulse duration on time (μs)	100–400
Current (A)	5–20
Duty factor (%)	50
Machining time (min)	40

2.2Characterization of the Surface Modification

The top surface and the cross-sectional morphologies of the layer were examined by Field Emission Scanning Electron Microscope (FE-SEM, JSM-7800F, JEOL, Japan). A cross-section of the machined workpiece was cast in resin in a mold. Flat edge filler was added to the resin to reduce the contraction of the resin. Prior to examining the cross-section by SEM, the cross-sectional layer was polished by abrasive paper number 180–1200, then a soft cloth and finally with 0.1 μm alumina powder. The surface layer was examined by EDS in order to investigate the chemical composition. The compound investigation of the modified surface was examined by XRD with CuKα radiation (Rigaku, Japan).

2.3 Average Roughness Surface Measurement

Table 4: Experimental Conditions for Average Surface Roughness Measurement

Experiment	Current (A)	Time-on (μs)
1	5	100
2	5	200
3	5	400
4	10	100
5	10	200
6	10	400
7	20	100
8	20	200
9	20	400

The average surface roughness (R_a) of the layer surface was evaluated after varying the current (I) and time-on (T_{on}) parameters. The parameters of voltage, duty factor and EDM time were fixed as 250 V, 50% and 40 minutes, respectively. The conditions in the experiments for average surface roughness measurement are shown as Table 4, and the experiments were randomly performed.

2.4 Mechanical Property Measurement

The mechanical property was measured in terms of microhardness testing. The microhardness was tested on a cross-section of surface layer by Micro Vickers Hardness Tester with an indentation load of 25 gf for 10 seconds.

3. RESULTS AND DISCUSSIONS

3.1 Morphology, Elemental Analysis and Phase Composition of Surface Modification

The X-ray diffraction analysis result of surface modification is shown in Figure 2. From the X-ray diffraction pattern, phase composition of aluminium titanium nitride (as $AlTi_3N$) was identified. The phase composition of AlTiN would have come from the workpiece (Al), electrode (Ti) and dielectric fluid (N). No hydrogen, oxygen and other elements compounds were found in the phase composition since they were probably so small in amount that they may have been beyond the detection limit of XRD. There are some phases of titanium aluminium nitride (as $Ti_3Al_2N_2$) and TiC, but they are not prominent in the pattern.

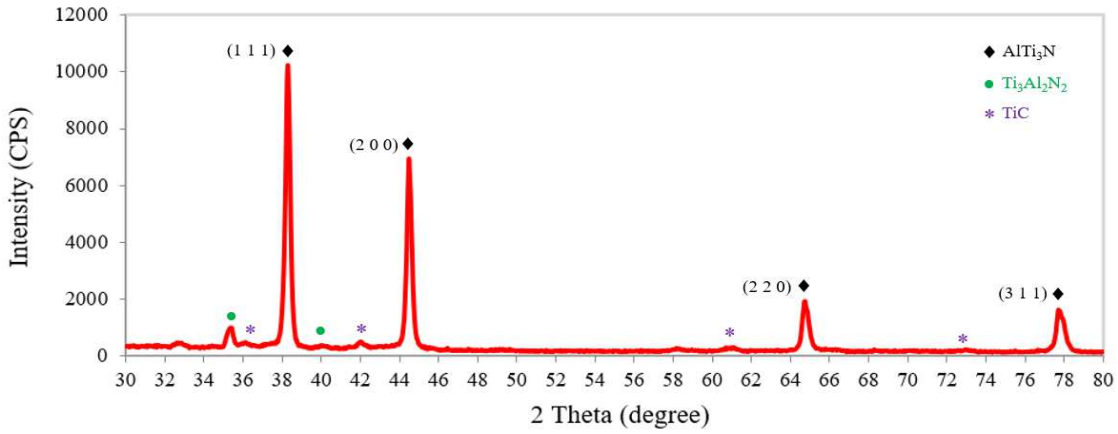


Figure 2: X-ray Diffraction Pattern.

During the EDM operation, an enormous amount of thermal energy was expended in the process, leading to the thermal decomposition of the dielectric fluid, monoethanolamine. The chemical reactions were probably as the equations below:

$$2OHCH_2CH_2NH_2 \rightarrow 2CO\uparrow + CH_4\uparrow + NH_3\uparrow + HCN + 3H_2\uparrow \quad (1)$$

$$2CO \rightarrow CO_2\uparrow + [C] \quad (2)$$

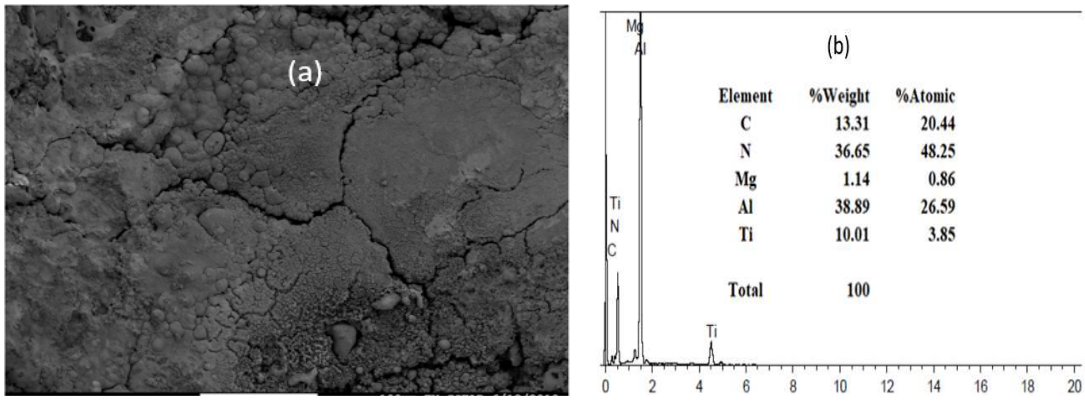
$$CH_4 \rightarrow 2H_2\uparrow + [C] \quad (3)$$

$$2NH_3 \rightarrow 3H_2\uparrow + 2[N] \quad (4)$$

$$2HCN \rightarrow H_2\uparrow + 2[C] + 2[N] \quad (5)$$

The chemical equations show the results of active C and N atoms in EDM process. N atoms chemically react with Ti atoms and Al atoms discharged from the tool electrode and workpiece respectively, forming an AlTiN/TiAlN coating on the substrate surface. TiC can also be formed by reaction between C atoms and Ti from the tool electrode. The 2-theta degree of pattern coincides to the planes of (111), (200), (220) and (311) of AlTiN detected by XRD, demonstrating the surface modification of AlTiN on the machined surface. The formation of composition can be attributed to very high temperature at the closest points between the electrode and workpiece heating the materials to the vaporization point. Each sparking is very hot and in a small area, thus the dielectric fluid can rapidly cool both the electrode and the workpiece as well as the vaporized material. From this phenomenon, it is possible for metallurgical changes to occur from the spark heating on the workpiece surface [16].

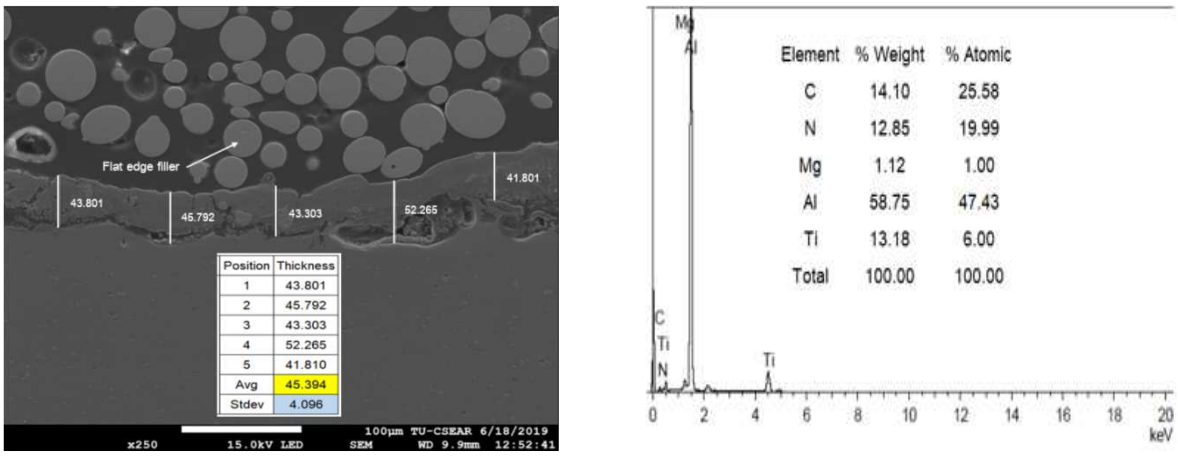
Figure 3 shows the SEM image of the top surface and its element analysis spectrum by EDS. The morphology of the top surface (Figure 3a) mainly consists of some ridges, microvoids and microcracks. The ridge areas are formed by melted materials which are heated in EDM process, and burst out of the surface by discharge pressure, and are then rapidly returned to solid state or solidification by cooling in dielectric fluid when the spark is turned off [16, 17]. The microvoids can occur by molten materials expelling gas bubbles out in the EDM process during solidification. Furthermore, it is conceivable that the microvoids can be generated because of the inhomogeneous solidification while materials are forming during the EDM process [17,18]. It has also been found that microcracks appear on the modified top surface. The pulse current and pulse time-on duration parameters have influence and affect the microcracks. These microcracks probably come from the results of thermal stress and inconstant temperature. The severe heating and cooling rates including nonuniform temperature distribution are causes of residual stress [17].Figure 3b shows the EDS elemental analysis spectrum and the percentages of each element on the surface after EDM. Additionally, the EDS result reveals that the elements correspond to the XRD patterns of AlTiN, TiAlN and TiC compounds.



(a) **(b)**

Figure 3: The Top Surface Morphology (a) and its Element Analysis Spectrum (b) Obtained by SEM and EDS Respectively.

Figure 4 shows the cross-sectional image of the modified surface by SEM (Figure 4a) and the element analysis spectrum by EDS (Figure 4b). A layer of AlTiN was created on the aluminium alloy substrate. Its thickness averaged about 45 microns. Figure 4b shows the element analysis result on the cross-section surface that supports the AlTiN layer. The layer shows inhomogeneous solidification and was obviously formed on aluminium alloy substrate. Micro cracks and micro voids were also generated on the cross-sectional layer.



(a) **(b)**

Figure 4: The Cross-Sectional Image (a) and its Element Analysis Spectrum (b) Obtained by SEM and EDS Respectively.

3.2 Average Surface Roughness Measurement

The average surface roughness (R_a) of the layer surfaces were measured by the surface texture measuring instrument, Olympus Laser Confocal Microscope, model OLS5000. The length of measurement was about 1,280 microns. The current and time-on parameters were varied and the experimental results were evaluated. The results of each surface roughness sample are shown in Figure 5–13, and a summary is shown in Table 5.

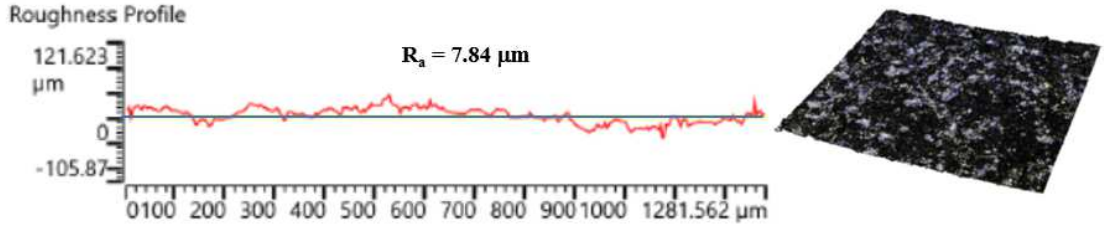


Figure 5: Roughness Profile of I = 5 A and T_{on} = 100 µs.

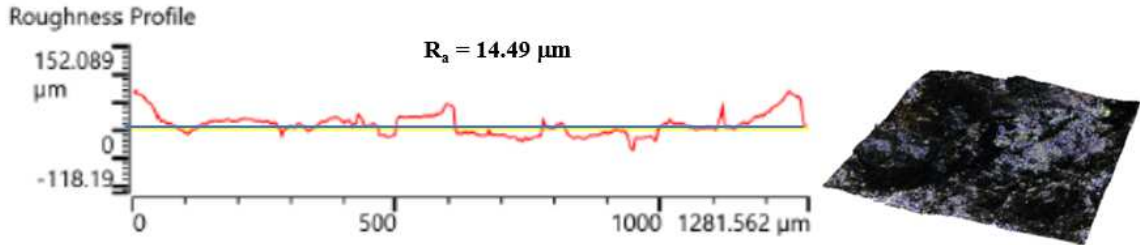


Figure 6: Roughness Profile of I = 5 A and T_{on} = 200 µs.

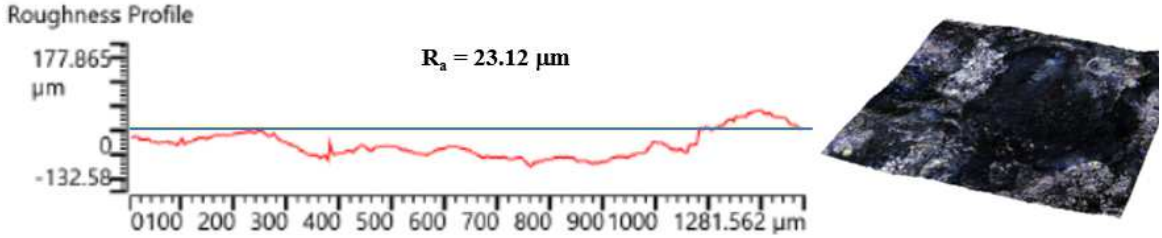


Figure 7: Roughness Profile of I = 5 A and T_{on} = 400 µs.

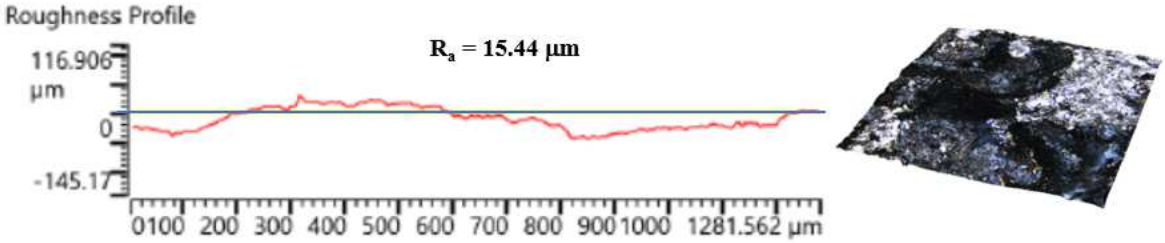


Figure 8: Roughness Profile of I = 10 A and T_{on} = 100 µs.

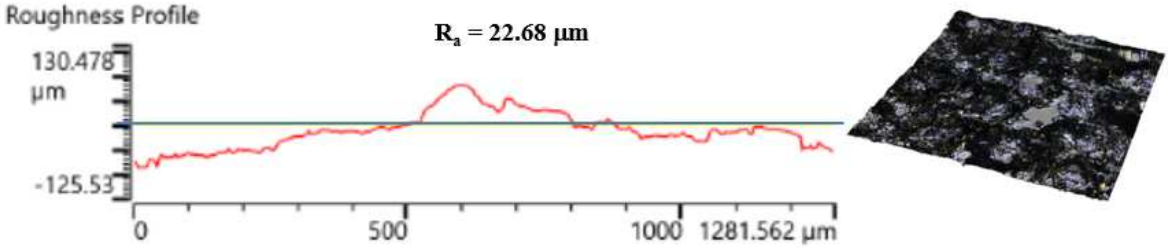


Figure 9: Roughness Profile of I = 10 A and T_{on} = 200 µs.

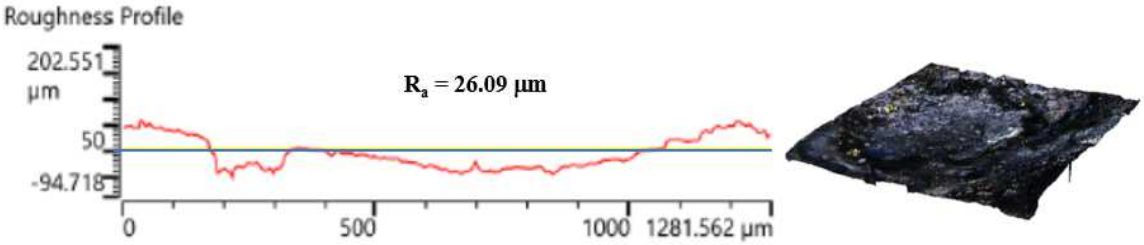


Figure 10: Roughness Profile of I = 10 A and T_{on} = 400 µs.

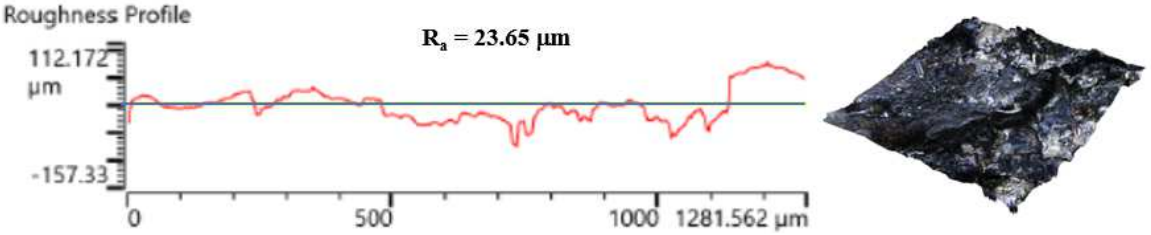


Figure 11: Roughness Profile of I = 20 A and T_{on} = 100 µs.

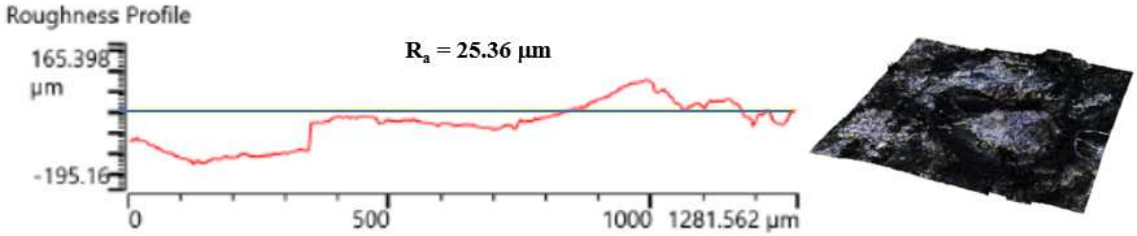


Figure 12: Roughness Profile of I = 20 A and T_{on} = 200 µs.

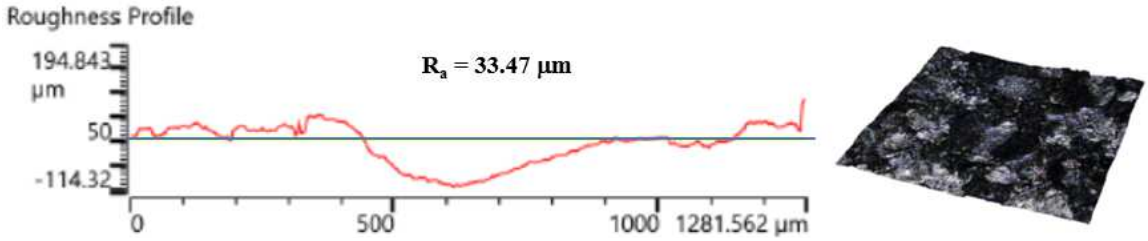


Figure 13: Roughness Profile of I = 20 A and T_{on} = 400 µs.

Table 5: Summary of Surface Roughness Measurement Results

Experiment	Current (A)	Time-on (µs)	Average Surface Roughness (µm)
1	5	100	7.84
2	5	200	14.49
3	5	400	23.12
4	10	100	15.44
5	10	200	22.68
6	10	400	26.09
7	20	100	23.65
8	20	200	25.36
9	20	400	33.47

When current is fixed and time-on is increased, R_a tends to increase. R_a also tends to increase when time-on is fixed and current is increased. These results may come from heat increment when current or time-on is increased. When the heat is increased in EDM process, severe reaction at high temperature and increasing erosion occur, resulting in deep pits or voids and affect the average surface roughness increment [10,18,19].The relationship of R_a versus current and time-on are shown in figure 14 and 15, respectively.

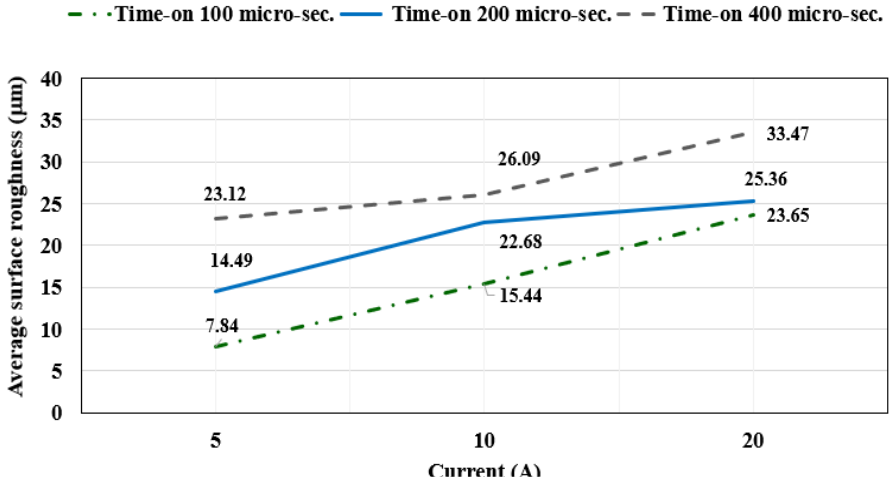


Figure 14: Average Surface Roughness of the Layer Surface by Current (A).

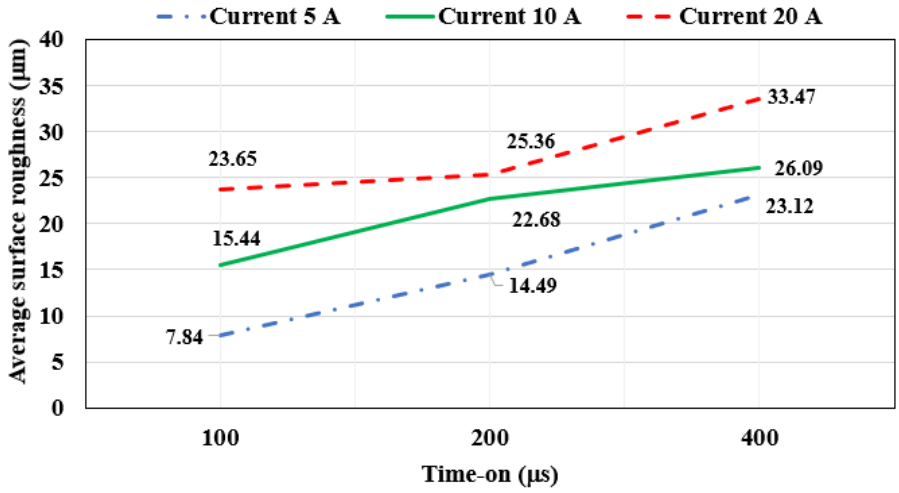


Figure 15: Average Surface Roughness of the Layer Surface by Time-on (µs).

3.3 Micro Hardness Testing

The microhardness testing was performed on the cross-sectional area by the Micro Vickers Hardness Tester with an indentation load of 25gf for 10 seconds. Figure16 shows the distribution of microhardness testing along with the cross-sectional area of the layer and the aluminium alloy substrate. The major component of the layer was AlTiN compound based on XRD pattern. The highest value of microhardness was 1355 HV, which appeared about 30 microns away from the machined surface, while the value of microhardness on the aluminum alloy substrate was about 81–89 HV.Figure17 shows the locations of microhardness testing, both of the modified layer and the aluminium alloy substrate.

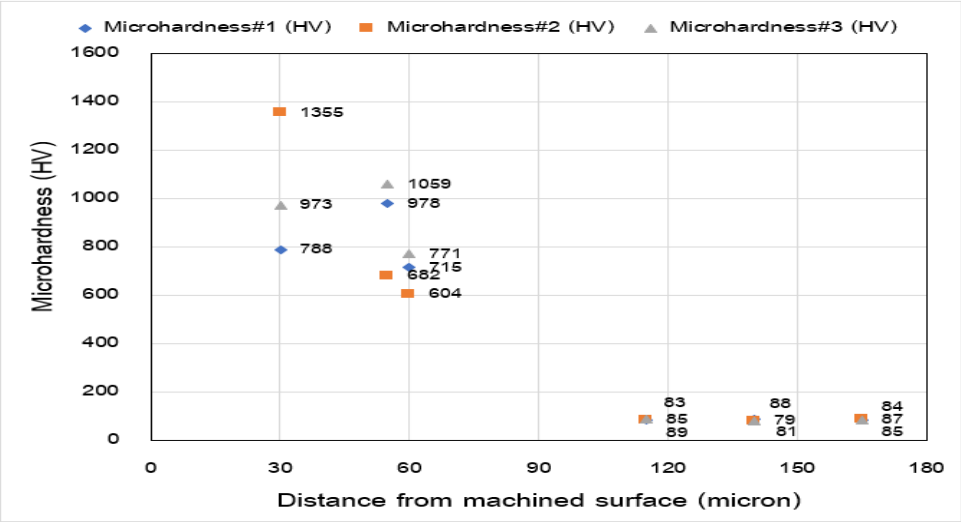


Figure 16: Micro Hardness Distribution along with the Cross-Sectional Area of the Layer and the Aluminium Alloy Substrate.

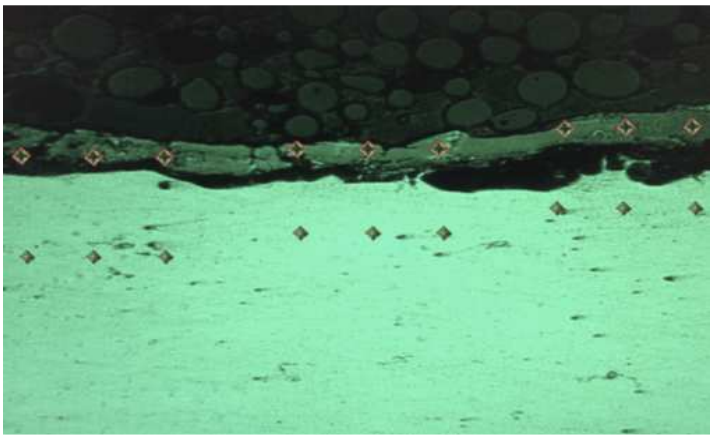


Figure 17: The Location of Micro Hardness Testing Area.

4. CONCLUSIONS

Surface modification on aluminium alloy substrate by EDM using titanium electrode in dielectric fluid of monoethanolamine was studied. In addition, the average surface roughness of surface layer and microhardness are also studied and investigated. The following conclusions were obtained:

- The recast layer thickness was about 45 microns.
- The top surface modification had some ridges, micro cracks and micro voids.
- The recast layer had inhomogeneous solidification with micro cracks and micro voids on the cross-sectional layer.
- The average surface roughness on the top surface (R_a) tended to increase when current or time-on was increased.
- The highest microhardness test result was 1355 HV that should be attributed to the combination of AlTiN particle reinforcement, while the value from microhardness testing on the aluminium alloy substrate was about 81–89 HV.

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Scholarship by National Science and Technology Development Agency (NSTDA), King Mongkut's Institute of Technology Ladkrabang (KMITL) and Seagate Technology (Thailand) Ltd. in 2010 – 2011 for study in Master of Engineering of Data Storage Technology (English Program) in International College at KMITL.

International Conference Publication

Voravit Nakwatananukool, Amporn Poyai, and Kasin Vichienchom, "Airborne Particles and Source of Contamination in Electrical Tester for HGA", DST-CON 2011, the 4th International Data Storage Technology Conference, Thailand.

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